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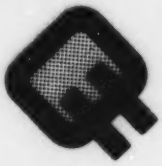

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# AN AUTOMATED AND COMPUTERIZED DILATOMETER SYSTEM TO MEASURE DEFORMATION MODULUS OF ROCK

Report No 84-330-K

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## ABSTRACT

An automated and computerized version of the Colorado School of Mines dilatometer system was adopted to assess excavation disturbance at the Underground Research Laboratory (URL) in Manitoba. This system highlights an intensifier operated by an electrically-driven hydraulic pump to allow controlled pressure loading and unloading of the dilatometer. This recently-developed system has satisfactorily provided deformation modulus values in high modulus rock, determined the extent of disturbance surrounding an underground opening and located open fractures within a rock mass.



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# AN AUTOMATED AND COMPUTERIZED DILATOMETER SYSTEM TO MEASURE DEFORMATION MODULUS OF ROCK

## 1.0 INTRODUCTION

An automated and computerized version of the Colorado School of Mines dilatometer system was adopted to assess excavation disturbance in the rock mass surrounding the shaft collar of an underground research laboratory (URL) in Canada. The eventual goal of determining the extent of blast and/or stress relief damage was to aid in shaft sealing designs for potential nuclear waste repositories. A previous study by Koopmans (1983) suggested that changes in bedrock moduli could be determined from plate bearing tests. Similarly, by conducting borehole dilatometer tests at relatively close intervals with distance from the shaft wall, a profile of the excavation disturbance represented by changes in deformation moduli could be determined.

## 2.0 LOCATION AND GEOLOGY

The testing program was undertaken within the shaft collar of an underground research laboratory (URL) located within the Lac du Bonnet batholith in south-eastern Manitoba, Canada (Figure 1). The batholith is elongated in shape and oriented in the ENE direction. Its approximate dimensions range up to 30 km in length and 25 km in width, covering an area of 1000 $km^2$. (Tammenagi et al, 1979).

Evidence has shown that the batholith is an intrusive and postdates both the adjacent Bird River greenstone belt and the Great Falls quartz diorite bodies. The batholith consists of a pink, massive, homogeneous quartz monzonite with numerous pegmatite and aplite dykes cutting through it. (Chagarlamundi, 1971). Based on air photo linement analysis and detailed surface fracture mapping, two main joint sets were detected. One set strikes in a northeast-southwest direction while the second set strikes in a northwest-southeast direction. Dipping of the joints is generally near vertical to vertical. Spacing of the joints ranges from 1 to 10 m with the average spacing for both major joint sets at approximately 3 m. (Tammenagi et al, 1979).

## 3.0 BOREHOLE MODULUS DETERMINATION

### 3.1 BACKGROUND

Panek et al (1964) developed a borehole dilatometer called the Cylindrical Pressure Cell (CPC) to determine the modulus of rigidity for rock. Due to certain operational problems such as permanent deformation of the copper membrane during pressurization in a borehole, Hustrulid and Hustrulid (1975) developed the Colorado School of Mines (CSM) cell to overcome some of the problems inherent in the CPC system. Testing by the authors (Koopmans and Hughes, 1983) indicated that the classical system of pressurizing the dilatometer using a manually-operated pressure generator and taking readings by hand worked well in general, but was determined to be very labour intensive, time consuming and subject to human error. The major complaint of this system has been leakage, which occurred both in the dilatometer itself and in the pressure generator. Leakage problems, which have also been reported by Patricio and Beus (1976), have been overcome by the authors (Koopmans and Hughes, 1983). This was accomplished by using vacuum grease on the membrane ends of the dilatometer and replacing the teflon seals in the pressure generator with molybdenum impregnated polyurethane seals.

The automated and computerized dilatometer system was developed to overcome the limitations indicated above. The system (Figure 2) highlights an intensifier operated by an electrically-driven hydraulic pump to allow controlled pressure loading and unloading of the dilatometer. The intensifier has a 6:1 piston differential ratio between the oil and water chambers, respectively. This allows lower oil pressures to be administered from the hydraulic pump through flexible hoses to the intensifier where the pressure is increased six times to allow water inflation of the dilatometer. As an option, a hand-operated hydraulic pump can be used in place of the electrical pump. This alteration would be especially useful when working in underground mines (ie coal) which might contain gases and make an electrical pump intrinsically unsafe. A second option which could be connected to the electric hydraulic pump is a servo-control unit which allows the operator to control the dilatometer loading and unloading from a remote location.

The intensifier has been built of high-strength steel with the water chamber prestressed by having an outer cylinder heated and shrunk over the main cylinder by cooling. This prestressing not only keeps the intensifier very portable, but improves the stiffness of the system by resisting relatively large internal water pressures. The stiffness of the testing system is extremely important and will be discussed in the subsequent section. A linear variance differential transformer (LVDT) has been fastened to the top of the intensifier and measures linear movement of the high pressure water piston during

loading and unloading. Linear movement represents volume change and is determined by calibration. A pressure transducer has also been connected to the water side just outside of the intensifier to measure changes in pressure. Both the LVDT and the pressure transducer have digital readout boxes to allow manual checking of readings during testing. Analog signals from both the LVDT and pressure transducer are sent to an A/D converter for conversion to digital signals and then into a computer. The computer stores the data on disc for later analysis, prints out the data in engineering units and plots the pressure-volume data points on an x-y plotter. Subsequent to testing, another computer program allows data reduction and the determination of deformation modulus values.

The dilatometer itself consists of a high-strength, stainless steel heat-treated shaft and an adiprene membrane capable of applying pressures in excess of 70 MPa. Lead beads or other fillers may be placed in the membrane cavity to reduce water volume and thereby increase the system stiffness. High-pressure, thick-walled tubing is used to connect the dilatometer to the intensifier.

The Mt/Ms ratio, which is the value of the pressure-volume slope for the pressurized system and rock divided by the stiffness value obtained for the pressurized system alone, is very important in the determination of the validity of modulus results. A sensitivity analysis performed by Hustrulid and Hustrulid (1972), concluded that an error margin of 20 per cent existed when the slope value for Mt was 96 per cent of Ms. The error percentage increases drastically as the numerator and denominator become nearly equal (ie the equation becomes undefined). In high modulus rock such as granite, it is very important that the Mt/Ms ratio is carefully checked in the field. The best method of improving the system stiffness is by removing or replacing (with a high modulus filler) water in the system.

## 3.2 CALCULATIONS

The complete derivations of equations required for the calculation of deformation modulus of rock is provided by Hustrulid and Hustrulid (1975). Only the basic equations are presented here. The only change in these equations is that calculations are now expressed as pressure-volume instead of pressure/turn. The intensifier moves in a linear direction and eliminates the need to read rotational turns inherent in the original CSM system. The systematic progression of calculations is shown in Figure 3.

Step 1 - The pressure-volume relationship (Mc) for the cylinder alone is calculated:

$$Mc = \frac{\gamma Gc}{\pi L\, r_{ic}^2 \left[\frac{1+\beta c}{1-\beta c} - \frac{2\mu c\ \beta c}{1-\beta c}\right]}$$

where: $\gamma$ = volume of fluid displaced
$Gc$ = modulus of rigidity of the calibration cylinder
$L$ = length of membrane
$\beta c = (r_{ic}/r_{oc})^2$
$r_{ic}$ = inner radius of calibration cylinder
$r_{oc}$ = outer radius of calibration cylinder
$\mu$ = Poisson's ratio

Step 2 - The slope of the pressure-volume curve (Mm) for the system plus the calibration cylinder is determined.

Step 3 - The stiffness of the pressurizing system (Ms) alone is calculated:

$$Ms = \frac{Mc\ Mm}{Mc - Mm}$$

Step 4 - The slope of the pressure-volume curve (Mt) for the pressurized system plus rock is determined.

Step 5 - The pressure-volume relationship (Mr) for the rock alone is calculated:

$$Mr = \frac{Ms\ Mt}{Ms - Mt}$$

Step 6 - The modulus of rigidity (Gr) is calculated:

$$Gr = \frac{Mr\ \pi Lr^2}{\gamma}$$

Step 7 - The deformation modulus (E) can be calculated if Poisson's ratio ($\mu$) is known (or can be assumed):

$$E = 2(1 + \mu)\ Gr$$

Only the straight line portions of the pressure-volume curves are utilized in the determination of Mm and Mt (Figure 4). The initial curved portions of the graphs are neglected since they represent the closure of fractures and the seating of the adiprene membrane.

### 3.3 TESTING PROCEDURE

Four horizontal Ex boreholes were tested in the shaft collar to depths of approximately 15 metres. The first five metres were tested at 0.25 metre intervals, while the next ten metres were tested at one metre intervals due to time constraints. A total of approximately 30 tests were thereby conducted in each borehole. One borehole plus calibrations could thus be tested in an eight- to ten-hour shift.

Prior to testing, the dilatometer was calibrated in both an aluminum and steel thick-walled cylinder. Each cylinder had an inner diameter of 3.81 cm, an outer diameter of 11.44 cm and an overall length of 30.48 cm. Six cycles were run for each calibration with the last five recorded. The first cycle was used to seat the dilatometer in the cylinder. After calibration, the dilatometer was placed at the bottom of the borehole using placement rods. Once again, six cycles were used with the last five recorded. Due to the very small volume changes which occur within the dilatometer, especially in high modulus rocks, it was determined that more accuracy could be obtained by averaging the slopes of the five curves together. Pressures in the order of 2 MPa were used to seat the dilatometer while pressures of approximately 25 MPa were used at the top of each cycle. Borehole testing progressed by moving the dilatometer from the bottom of the borehole towards the collar. Upon completion of testing the borehole calibrations were taken once again to verify the original calibrations. With the aid of a computer, both pressure and volume were recorded every two seconds and stored on floppy disc. At the same time, the points were both plotted and printed out to enable immediate analysis as desired. A typical run for a borehole test is shown in Figure 4. The figure also shows the slope used in the determination of deformation modulus. The straight line portion between 15 and 25 MPa was selected as having the most elastic behaviour. The slope was determined by using the least squares method for each of the five runs and averaging them together with the aid of a computer. Another computer program was then used to determine the deformation modulus. The results of all test locations were then plotted to show the profile of deformation modulus with depth for each borehole. (Figures 5 to 8).

### 3.4 DISCUSSION OF RESULTS

The calculated deformation modulus results for each borehole are shown in Table 1 and the borehole profiles are shown in plan view around the shaft in Figure 9. In general, each borehole shows a tendency for the deformation modulus to increase with depth from the shaft wall and level out at a constant value between one and two shaft diameters (ie, 4 to 8 metres). Where individual test results have been plotted, it can be noted that low deformation moduli

represent fractures intersecting the borehole (Figure 5). Fractures designated as known fractures were verified by vacuum permeability measurements (Jakubick, 1984) or by impressions made with the borehole dilatometer wrapped with electrical tape. The cause for the undulating appearance of the profiles close to the shaft wall is not known for certain but is probably due to stress changes in the disturbed zone. Further testing is required before definite conclusions can be drawn. A comparison of deformation modulus results with other techniques is shown in Table 2. Average results for the dilatometer testing in all four boreholes is 54 to 63 GPa in the elastic zone of the rock mass including fractures and 63 to 67 GPa in the elastic rock mass excluding fractures. Cross-hole ultrasonics provided values in the order of 65-70 GPa for the rock mass surrounding the shaft (Wong et al, 1984). Average values for both biaxial cell testing (Koopmans, 1982) and uniaxial compression testing (McKay, 1982) were determined for samples obtained from borehole URL-1 which is located near the URL shaft. These results were 54 GPa and 73 GPa, respectively. The comparison indicates that the dilatometer results obtained were very good especially when one considers that dynamic testing and compression testing of good quality core samples typically provide higher modulus values than static insitu testing.

## 4.0 CONCLUSION

The automated and computerized dilatometer has satisfactorily provided deformation modulus values in high modulus rock, determined the extent of excavation disturbance surrounding an underground opening and located open fractures within a rock mass. A prominent feature of the system is the ability to collect and analyze data rapidly and accurately under field conditions. A comparison of dilatometer test results with other techniques used to obtain deformation modulus results agree quite favourably. At the present time, interpretation of the profile within the disturbed zone is inconclusive and requires further testing and analysis of results.

## ACKNOWLEDGEMENTS

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## TABLE 1

## DEFORMATION MODULUS WITH DEPTH FOR ALL BOREHOLES

| Depth (m) | Deformation Modulus (GPa) | | | |
|---|---|---|---|---|
| | N1 | N2 | S3 | S4 |
| 0.25 | 29 | 59 | 35 | 25 |
| 0.50 | 37 | 48 | 41 | 44 |
| 0.75 | 43 | 56 | 59 | 36 |
| 1.00 | 47 | 43 | 42 | 28 |
| 1.25 | 34 | 38 | 36 | 28 |
| 1.50 | 32 | 46 | 49 | 41 |
| 1.75 | 39 | 47 | 51 | 50 |
| 2.00 | 54 | 38 | 44 | 51 |
| 2.25 | 25 | 46 | 51 | 47 |
| 2.50 | 50 | 46 | 42 | 46 |
| 2.75 | 47 | 55 | 37 | 42 |
| 3.00 | 50 | 55 | 47 | 44 |
| 3.25 | 52 | 59 | 57 | 54 |
| 3.50 | 44 | 68 | 55 | 45 |
| 3.75 | 28 | 68 | 52 | 60 |
| 4.00 | 29 | 57 | 56 | 61 |
| 4.25 | 28 | 56 | 63 | |
| 4.50 | 49 | 49 | 62 | |
| 4.75 | 26 | 46 | 64 | |
| 5.00 | 50 | 44 | 60 | 49 |
| 6.00 | 50 | 48 | 65 | 44 |
| 7.00 | 40 | 61 | 59 | 49 |
| 8.00 | 74 | 81 | 64 | 60 |
| 9.00 | 11 | 21 | 62 | 40 |
| 10.00 | 56 | 55 | 64 | 63 |
| 11.00 | 56 | 68 | 60 | 69 |
| 12.00 | 44 | 62 | 58 | 76 |
| 12.50 | | | 71 | |
| 13.00 | 77 | 57 | | 72 |
| 14.00 | 59 | 43 | | 63 |
| 15.00 | 72 | 56 | | |

TABLE 2

COMPARISON OF DILATOMETER RESULTS WITH OTHER TECHNIQUES

| Technique | Borehole | Average Deformation Modulus (GPa) Including Rock Mass Fractures | Average Deformation Modulus (GPa) Excluding Rock Mass Fractures | Reference |
|---|---|---|---|---|
| Borehole Dilatometer | N1 | 54 | 64 | This Report |
| " | N2 | 56 | 63 | " |
| " | S3 | 63 | 63 | " |
| " | S4 | 63 | 67 | " |
| Cross-Hole Ultrasonics | N1-N2 | 65-70 | | Wong, Hurley and West, 1984 |
| | S3-S4 | | | |
| Biaxial Cell | URL-1 | | 54 | Koopmans, 1982 |
| Uniaxial Compression | URL-1 | | 73 | McKay, 1982 |

Note: URL-1 is located near the URL shaft

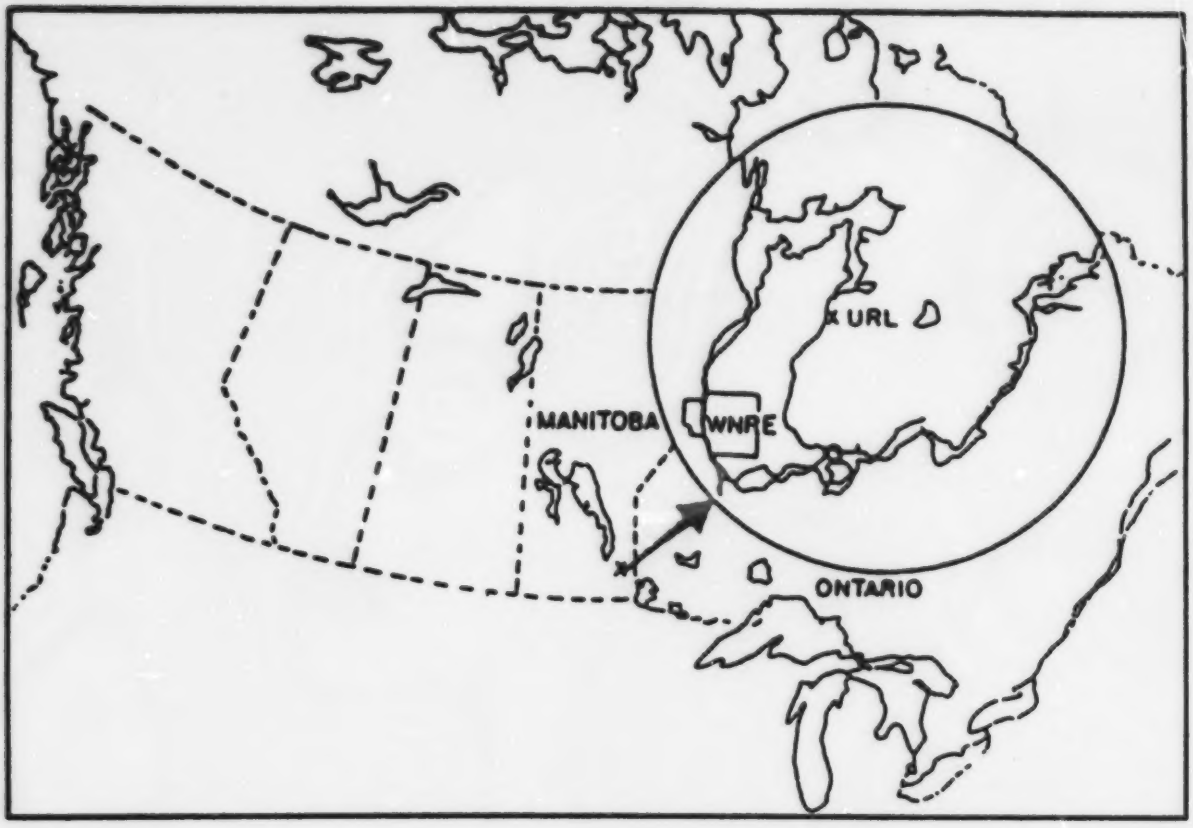


FIGURE 1
LOCATION OF URL TEST SITE

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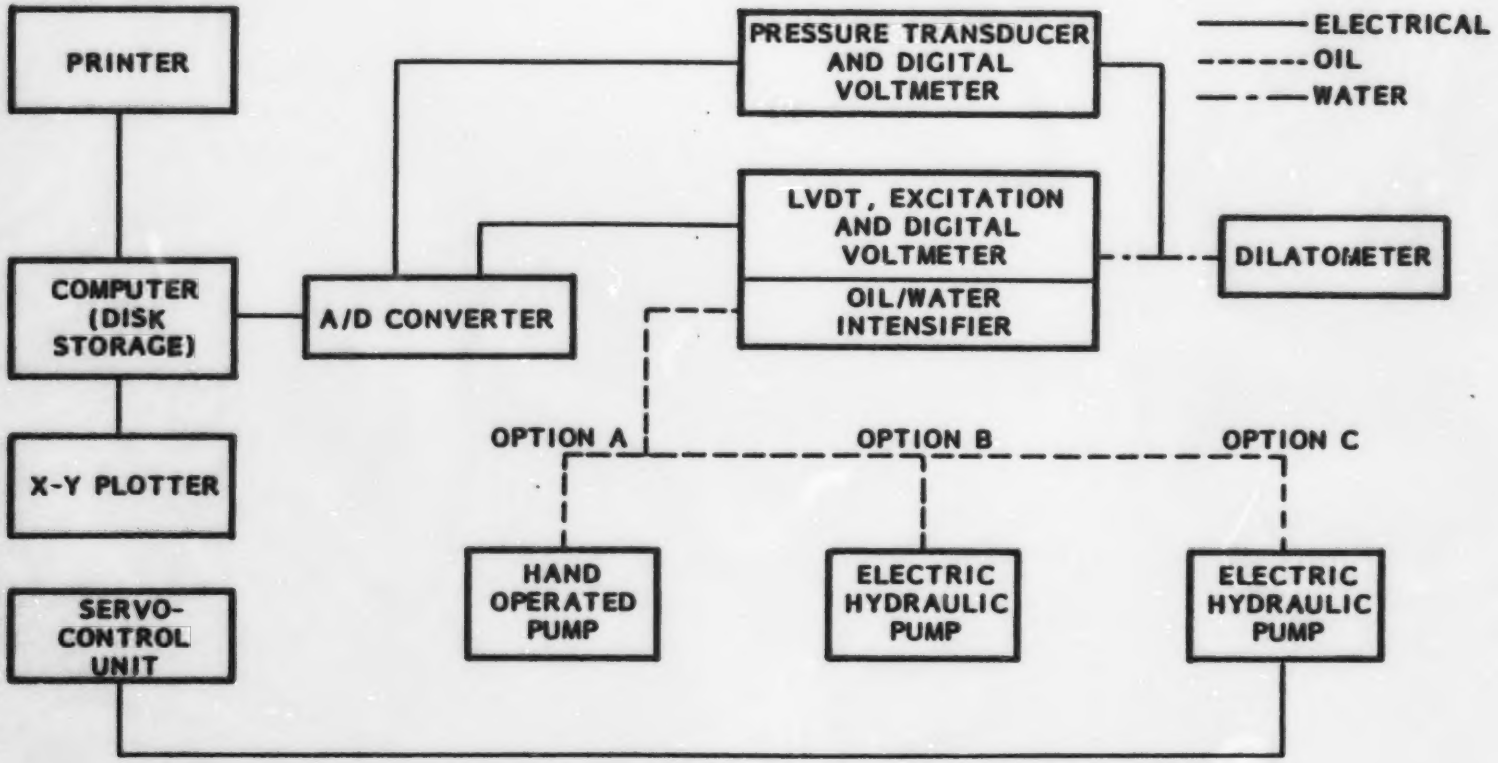


FIGURE 2

SCHEMATIC OF AUTOMATED COMPUTERIZED DILATOMETER SYSTEM

166659 RD

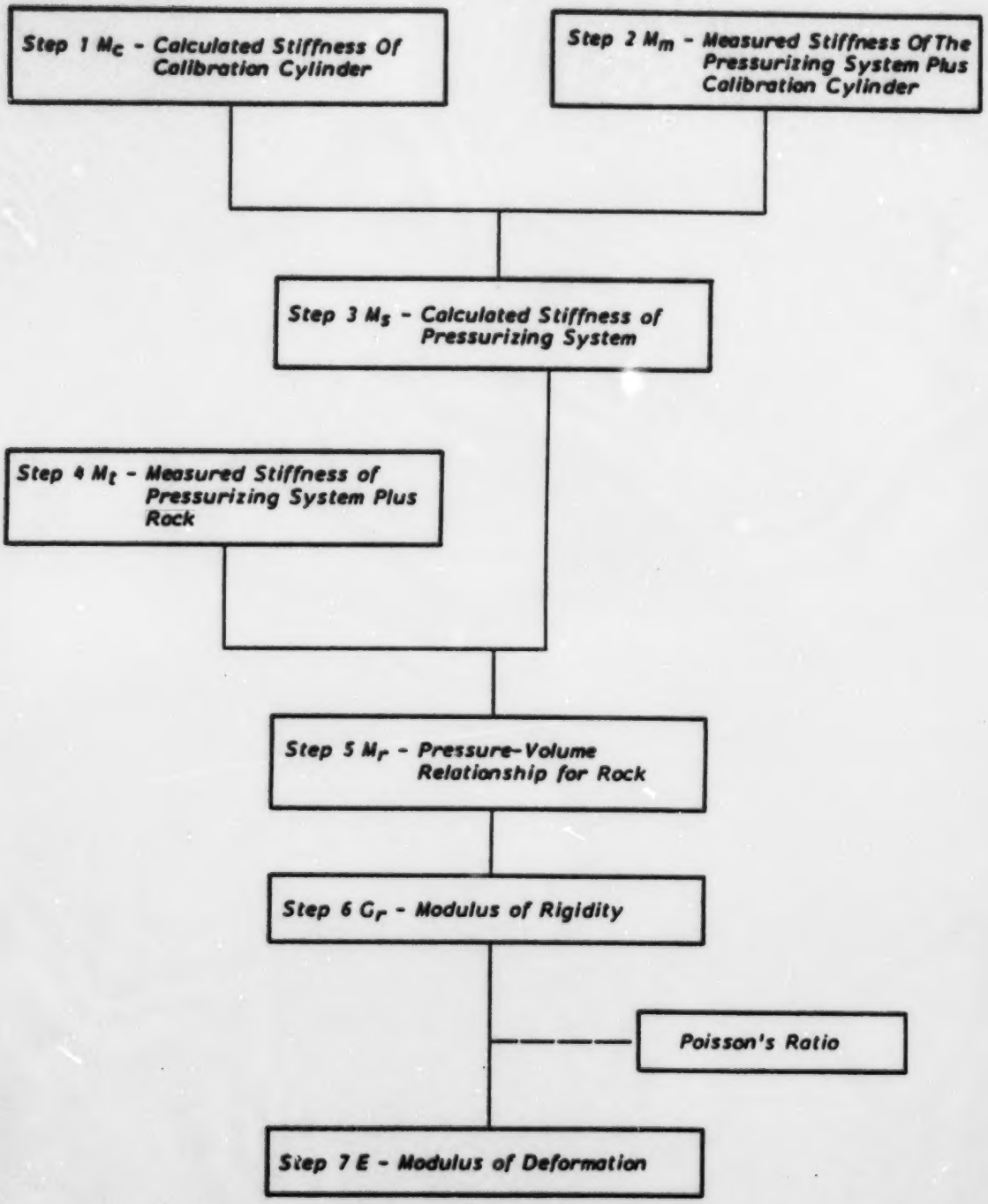
Step 1 $M_c$ - Calculated Stiffness Of Calibration Cylinder
Step 2 $M_m$ - Measured Stiffness Of The Pressurizing System Plus Calibration Cylinder
Step 3 $M_s$ - Calculated Stiffness of Pressurizing System
Step 4 $M_t$ - Measured Stiffness of Pressurizing System Plus Rock
Step 5 $M_r$ - Pressure-Volume Relationship for Rock
Step 6 $G_r$ - Modulus of Rigidity
Poisson's Ratio
Step 7 E - Modulus of Deformation

FIGURE 3
SYSTEMATIC PROGRESSION OF CALCULATIONS

166660 RD

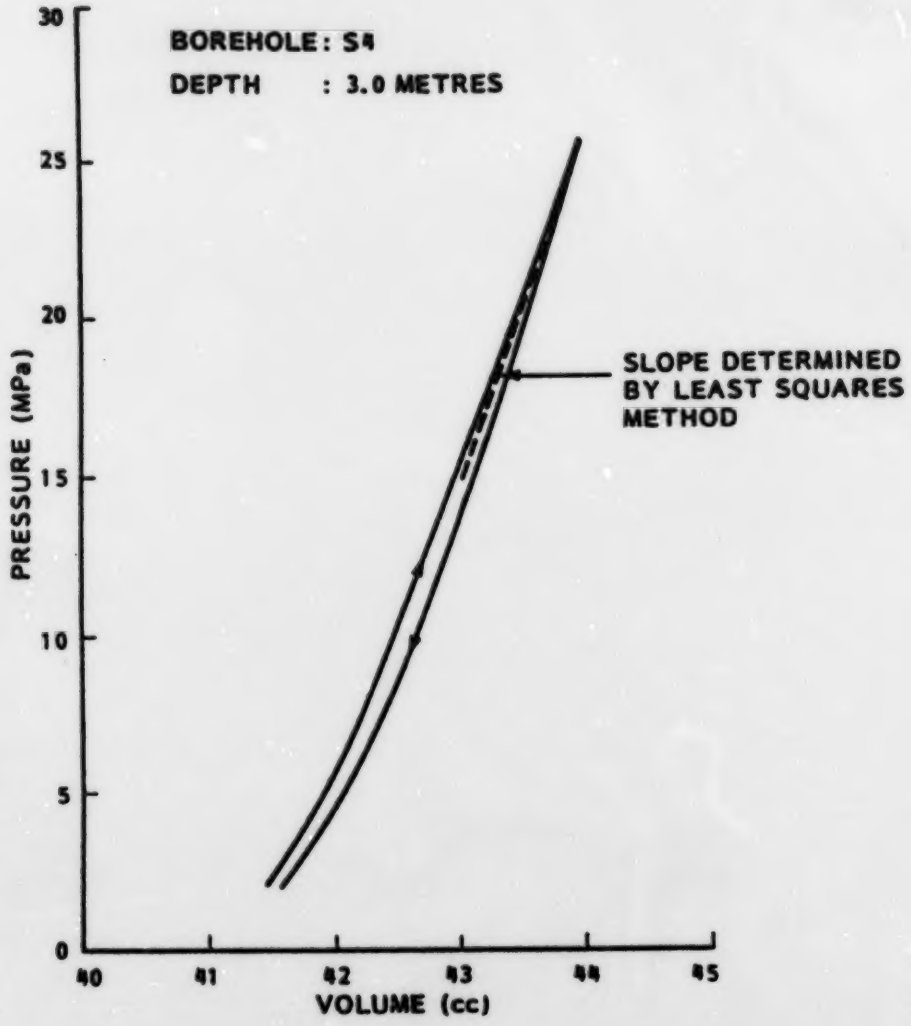


FIGURE 4

TYPICAL RUN FOR BOREHOLE TEST

166661 RD

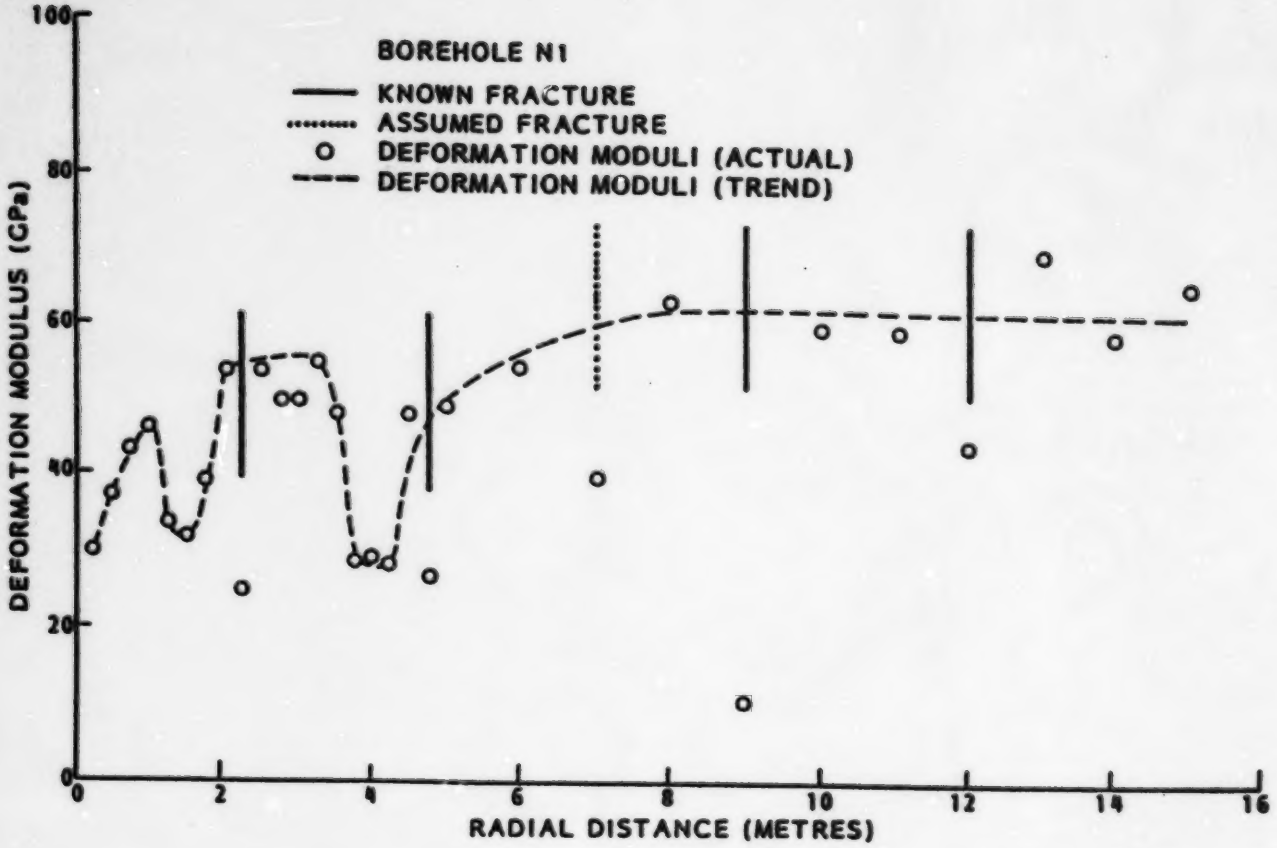


FIGURE 5

DEFORMATION MODULUS WITH DEPTH FROM SHAFT WALL

166662 RD

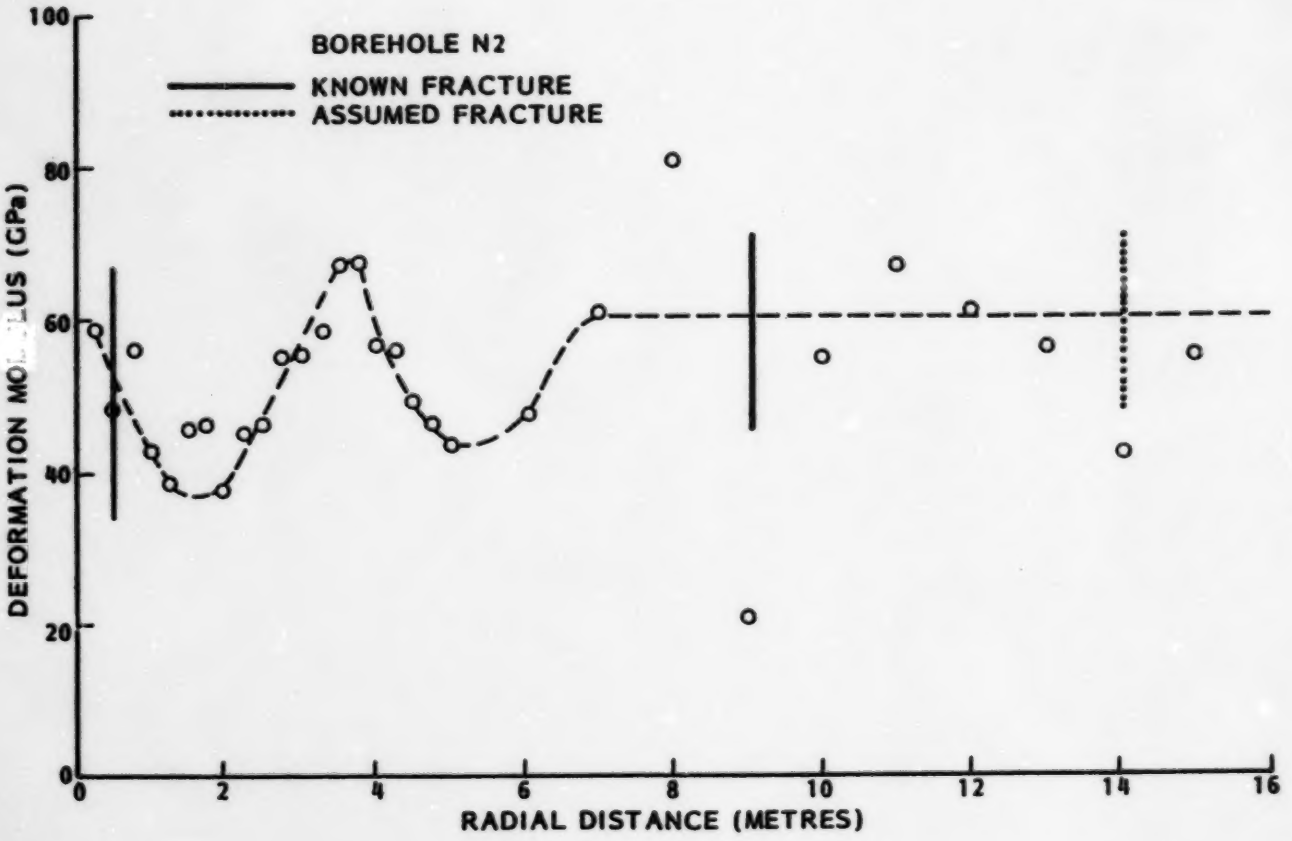


FIGURE 6

DEFORMATION MODULUS WITH DEPTH FROM SHAFT WALL



84-330
166694 RD

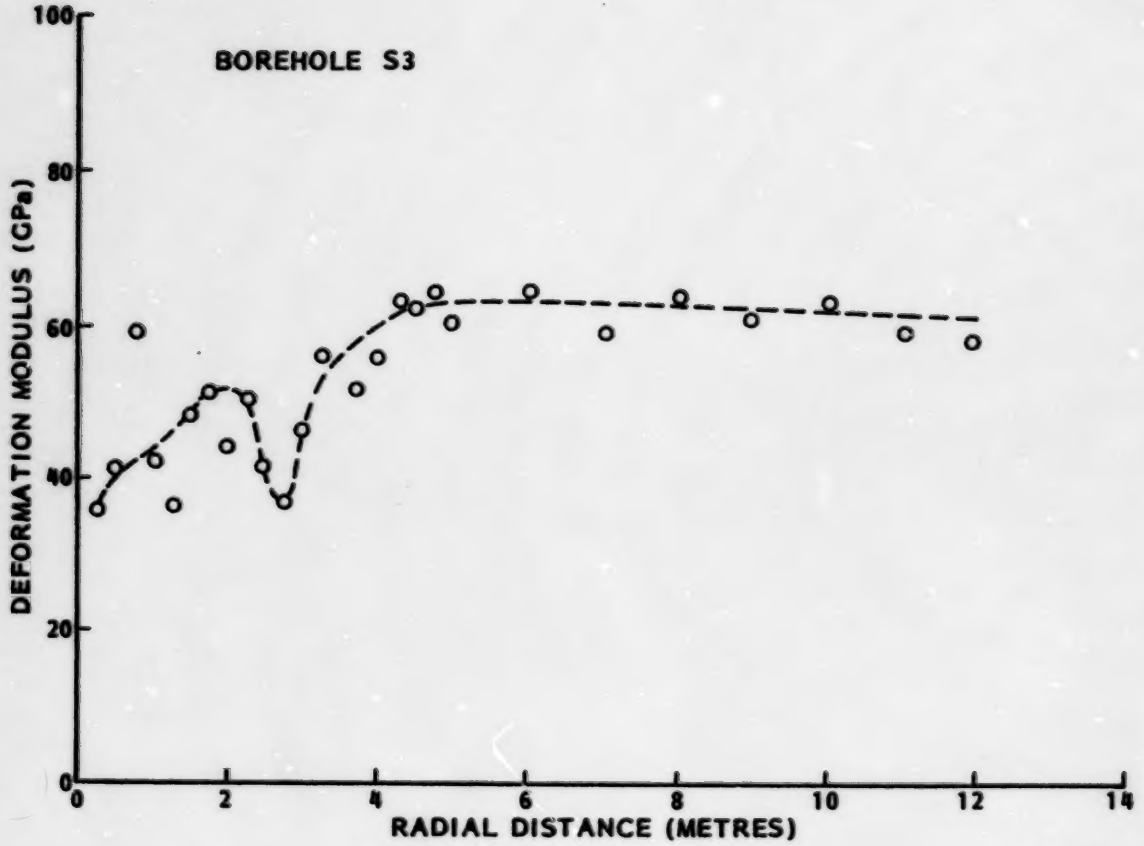


FIGURE 7

DEFORMATION MODULUS WITH DEPTH FROM SHAFT WALL

166663 RD

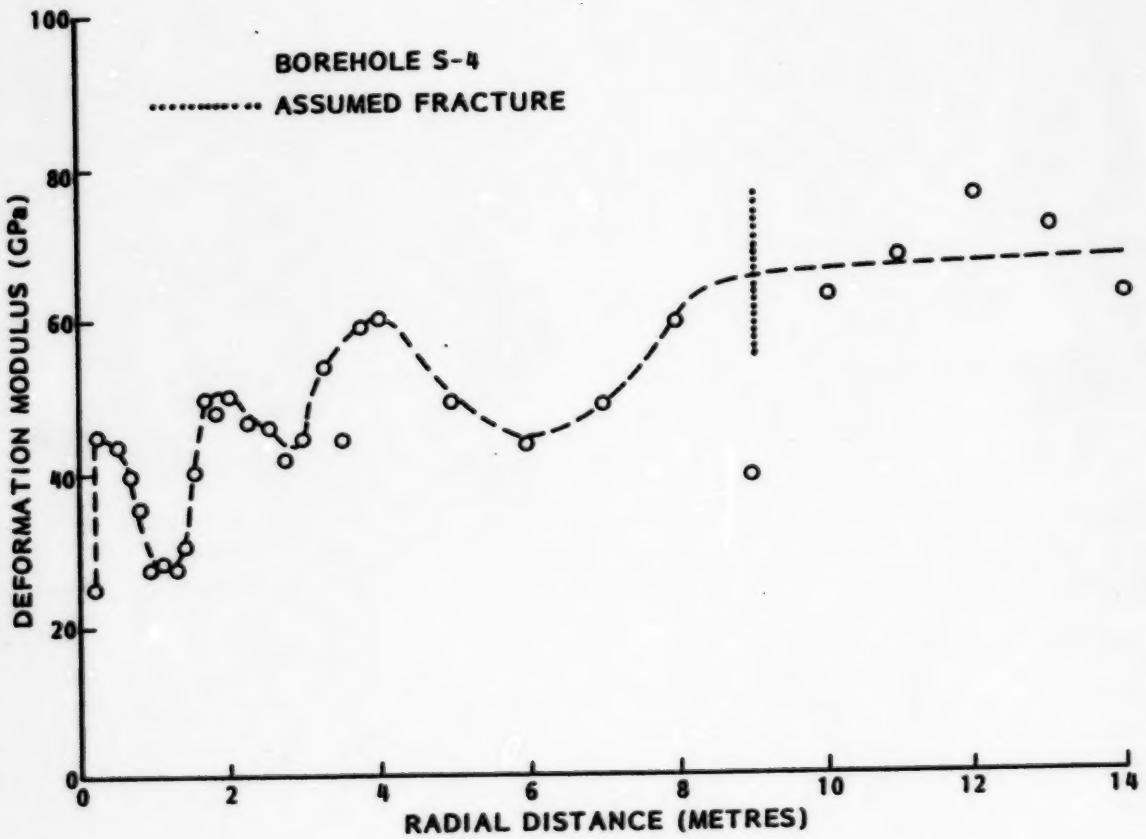


FIGURE 8

DEFORMATION MODULUS WITH DEPTH FROM SHAFT WALL

166665 RD

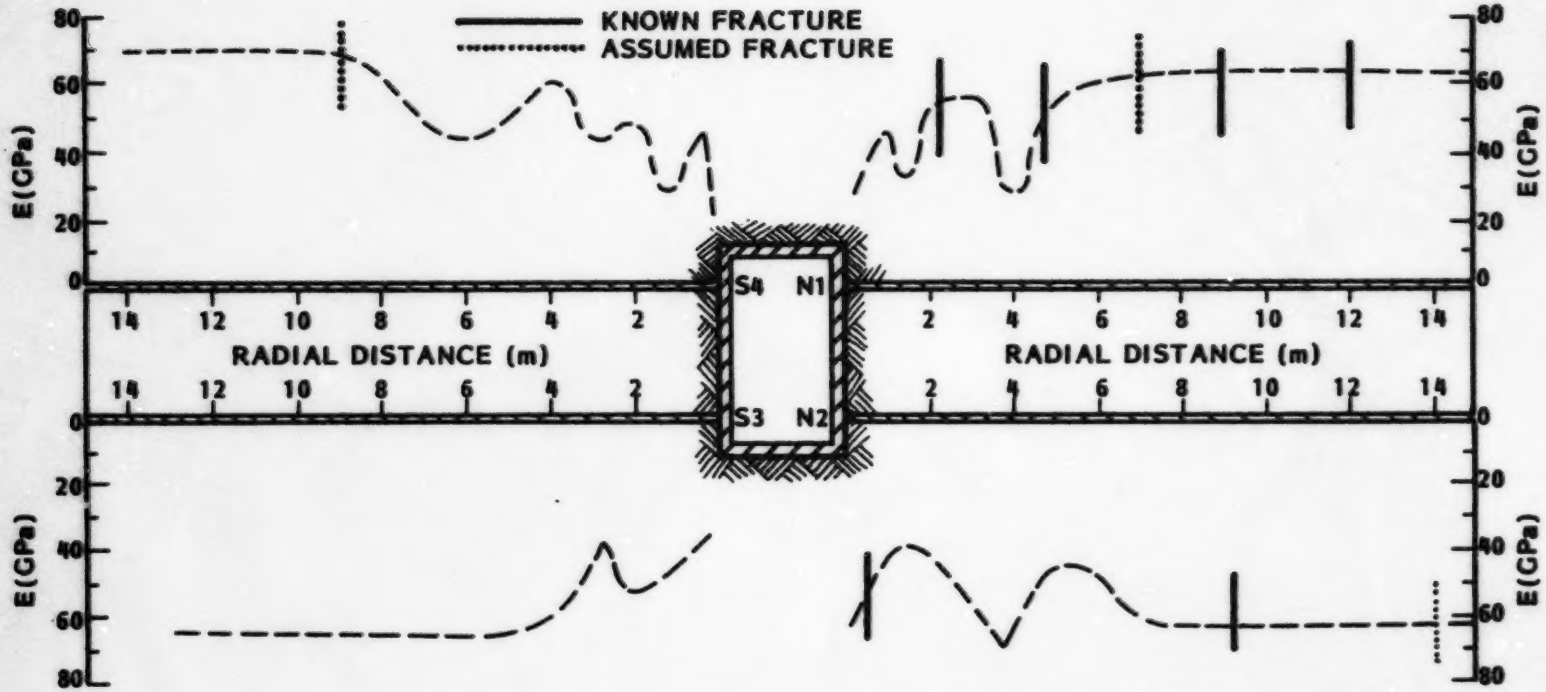


FIGURE 9
DEFORMATION MODULUS WITH DEPTH FROM SHAFT WALL



84-330
166666 RD